Journal of Experimental Psychology:
Learning, Memory, and Cognition
2008, Vol. 34, No. 3, 712–718

0278-7393/08/$12.00 DOI: 10.1037/0278-7393.34.3.712

Context-Sensitive Adjustments of Cognitive Control: Conflict-Adaptation Effects Are Modulated by Processing Demands of the Ongoing Task

Rico Fischer, Gesine Dreisbach, and Thomas Goschke
Technische Universität Dresden

Dynamic adjustments of cognitive control in response to interference from irrelevant stimulus attributes have repeatedly been shown. The purpose of the current research was to investigate how these control adjustments are modulated by the processing demands of a primary task. To this end, the authors combined a primary task (a number comparison task: classifying digits as smaller or larger than 5) with a Simon task. Control adjustments were observed in the form of typical sequential modulations of the Simon effect. In addition, the authors found sequential modulations of the numerical distance effect and an interaction of both effects. Results suggest that not only response conflict due to interference from task-irrelevant features but also processing demands of task-relevant features determine the level of control adjustment in the subsequent trial.

Keywords: cognitive control, conflict, Simon task, sequence effects

A fundamental ability of the cognitive system is to maintain current goal representations in the face of distraction. Selective attention enables us to select task-relevant stimulus features while suppressing distracting information, alternative goals, and competing response tendencies. Two central, yet unresolved, questions are how attentional resources are coordinated and how cognitive control processes, which serve to shield the cognitive system from distracting information, are flexibly adjusted to changing task demands (cf. Goschke & Dreisbach, 2008; Miller & Cohen, 2001). To date most studies on the context-sensitive adaptation of cognitive control have focused on the role of response conflict in triggering enhanced mobilization of cognitive control (e.g., Gratton, Coles, & Donchin, 1992; Kerns et al., 2004). *Response conflict* occurs whenever a stimulus comprises features that are associated with both the correct and the competing response. According to an influential theory (Botvinick, Carter, Braver, Barch, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004), response conflict in a given task induces enhanced mobilization of cognitive control on the subsequent trial of the task in order to prevent interference. Consistent with this hypothesis, research has shown that interference from distractors in speeded choice–reaction tasks is reduced on trials following response-incompatible (high conflict) trials, compared to trials following compatible (low conflict) trials (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Gratton et al., 1992; Kerns et al., 2004). Such conflict-adaptation effects suggest that response conflicts induce enhanced target processing and/or distractor suppression on the following trial (but see Mayr, Awh, & Laurey, 2003).

Here we investigated three hitherto open questions concerning the context-sensitive adjustment of cognitive control in selective attention tasks: (a) Is response conflict a necessary precondition for subsequent control adjustments to appear? Or is it possible to obtain similar control adjustments when processing demands in the primary task increase (cf. Dreisbach & Haider, 2006)? (b) How do differences in processing demands in the primary task affect the activation of (response) conflict-triggered control adjustments? (c) How do processing adjustments due to differential demands in a primary task interact with (response) conflict-induced control adjustments?[1]

To address these questions, we manipulated the attentional resource requirements in terms of different "processing modes" in a primary task and investigated their direct effects on the efficiency of the conflict-induced control adjustments. More specifically, we combined a number size judgment task, which served as the primary task, with a Simon task (Simon, 1990) that is known to induce robust response conflicts. Participants had to decide whether a given number was smaller (left key) or larger than 5 (right key). There is broad evidence that task demands in the number comparison task vary as a function of the numerical distance to the comparison level (e.g., Dehaene, Dupoux, &

Rico Fischer, Gesine Dreisbach, and Thomas Goschke, Department of Psychology, Technische Universität Dresden, Dresden, Germany.

This research was supported by the German Research Foundation (DFG) Grant Go 720/3-3. We thank Moritz Walser for data collection, John Dunlosky and Michael Masson for constructive comments on an earlier version of the article, and Franziska Plessow for valuable discussions.

Correspondence concerning this article should be addressed to Rico Fischer, Department of Psychology, Technische Universität Dresden, Zellescher Weg 17, Dresden, Germany 01062. E-mail: fischer@psychologie.tu-dresden.de

[1] For reasons of clarity, we use the term *processing adjustment* whenever differences in primary task processing requirements lead to adjustments of processing in the subsequent trial. In this respect, processing demands are supposed to imply that the effort or resource investment to successful task accomplishment may vary even within the primary task irrespective of additional task-irrelevant features. In contrast, we use the terms *conflict* or *control adjustment* when irrelevant stimulus features imposed conflicts that triggered control regulations, irrespective of primary task demands.

Mehler, 1990; Moyer & Landauer, 1967). Oriet, Tombu, and Jolicoeur (2005), for example, assumed that the mental representation of digits far from the comparison digit of 5 (e.g., 1 and 9) are tagged as "small" or "large" and are therefore precategorized as large or small in an automatic fashion. In contrast, size judgments for digits that are close to 5 rely on a slower and more controlled comparison process that requires resources. At the same time, presenting digits either to the left or right of the screen center induces stimulus–response compatibility (so-called *Simon interference*), leading to response conflict, when the irrelevant stimulus attribute (location) does not correspond with the required response to the relevant attribute (e.g., a small number presented at the right).

This allowed us to investigate whether and how different processing modes (more easy and automatic precategorization vs. more effortful and controlled comparison) in trial $N - 1$ (i.e., the numerical distance [ND] effect) modulate response-conflict-induced adjustment of cognitive control on the subsequent trial and vice versa: whether and how a response conflict in trial $N - 1$ modulates the ND-induced processing adjustment on the subsequent trial. On a more general level, we thus are interested in how the cognitive system coordinates the assignment of attentional control in the face of distraction from task-irrelevant stimulus features, on the one hand, and in the differential processing requirements during the processing of task-relevant stimulus features in the primary task, on the other.

Given our general assumption that any control and processing resources are coordinated to serve the goal of performing the primary task, we expect that a more effortful and controlled processing mode in the ND task (close numbers in trial $N - 1$) would bind attentional resources, which might be drawn from the pool needed for the sufficient activation of control adjustments following an experienced response conflict in Simon-incompatible trials $N - 1$. We thus assume that these dynamic adjustments of cognitive control on trial N (reflected in reduced Simon interference) are modulated by processing modes on trial $N - 1$. That is, the sequential modulation of the Simon effect (Notebaert, Soetens, & Melis, 2001; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Wühr & Ansorge, 2005) should be weaker when responding to close than to far digits on trial $N - 1$ (this should show up in a $\text{ND}_{N-1} \times \text{Simon}_N \times \text{Simon}_{N-1}$ interaction, which we refer to as $\mathit{ND}_{N-1} \times \mathit{Simon\text{-}modulation}_N$ hereafter).

Analogously, a response conflict due to Simon incompatibility in the previous trial $N - 1$ typically triggers adjustments of cognitive control that serve to reduce interference from irrelevant stimulus attributes (i.e., stimulus location) in the subsequent task in trial N. Now, two possibilities are conceivable as to how these control mechanisms might also alter the number comparison process in the primary task of trial N. First, a heightened recruitment of control, serving to reduce interference in trial N, might benefit all processes that are related to target processing (e.g., Egner & Hirsch, 2005). According to this possibility, the number comparison process should especially benefit from heightened control when categorizing close numbers (controlled processing mode). In contrast, it is possible that both control mechanisms compete for the same resources. From this perspective, the (Simon-induced) enhanced control, serving interference reduction, might even diminish the efficiency of the number comparison process, especially when processing close numbers, but less so when categorizing far numbers. In any case, a response conflict in $N - 1$ should modulate the ND effect in N (this assumption is reflected in a $\text{Simon}_{N-1} \times \text{ND}_N$ interaction). Note, however, that the direction of this interaction will distinguish between both possibilities.

Furthermore, if our assumption proves right and adaptations of cognitive control within selective attention tasks are not restricted to experienced response conflicts, then we should find sequential modulations of the ND (analogous to the Simon effect), resulting in a $\text{ND}_{N-1} \times \text{ND}_N$ interaction. A repeated application of the slower controlled comparison process, for example, should be effective when the subsequent target is again close but should lead to performance costs when the subsequent target is far from 5. This would result in a smaller ND effect. By contrast, when categorizing digits that are far from 5, a repeated application of the fast and automatic categorization process would result in benefits if the subsequent target is again far from 5, whereas costs should emerge when close digits follow. In conclusion, we expect a larger ND effect when the preceding trial contains far rather than close digits (i.e., an $\text{ND}_{N-1} \times \text{ND}_N$ interaction).

Method

Participants

Fifteen students (9 women, 6 men; mean age = 23.2 years) at the Technische Universität Dresden took part in the experiment. All had normal or corrected-to-normal vision. Participants attended a single experimental session lasting about 50 min and received a 5€ payment.

Apparatus and Stimuli

The numerals 1 to 9 (except 5) served as stimuli and were displayed on a 17-in. (43.18 cm) monitor. Stimuli were presented in Arabic notation 2.8 cm either to the left or to the right of a fixation (plus sign), which resulted in a visual angle of 2.7° to the left and right, respectively (viewing distance 60 cm). The digits were presented in white against a black background and subtended a visual angle of about 0.48° to 0.67°. Responses were made with the index finger of the right hand pressing the period (.) key or with the left index finger pressing the *y* key of the standard German (QWERTZ) computer keyboard.

Procedure

Participants were asked to categorize digits as either smaller or larger than 5. Instructions emphasized speed and accuracy to the same extent. Small numbers were responded to with the left index finger and large numbers with the right index finger. The stimulus response mapping was kept constant across participants.

Each trial began with the presentation of the fixation sign for 1,000 ms. Following a blank screen of 600 ms, a digit was presented for 200 ms. In the case of correct responses, a blank screen was provided as feedback for 300 ms. If no response was given 1,800 ms after stimulus onset, the feedback "zu langsam" (too slow) was shown. In the case of an incorrect response, an error feedback "Fehler" (error) was provided. Both kinds of feedback were displayed for 300 ms. Following either kind of feedback (blank, too slow, or error) the screen went blank for another 700 ms before the next trial started with the presentation of the fixation.

The 16 combinations of digits and locations were repeated four times per block (64 trials). Trial transition probabilities were controlled for a priori. The experiment consisted of 12 blocks that were separated by short breaks in which participants were encouraged to relax. Except for the first block, each block started with the presentation of the last trial of the previous block in order to keep transition probabilities equal and in order to provide an appropriate $N - 1$ history of the first trial (now the second trial) in the present block. For Blocks 2–12 this increased the number of trials to 65 per block. However, the first trial in each block was eliminated prior to analyses, which again resulted in 64 trials for Blocks 2–12 and in 63 trials in Block 1. Before the experiment, participants performed 16 practice trials.

Results

To minimize the possibility that the Simon modulation was driven by repetitions of identical trial events (Hommel, Proctor, & Vu, 2004; Mayr et al., 2003), we excluded all identical repetitions from the analyses (6.4%).[2] Erroneous trials (3.4%) and all trials in which reaction times (RTs) did not fit the outlier criterion (2.5 *SD*s; 2.3%) were also excluded prior to statistical analyses. A repeated measures analysis of variance (ANOVA) including the factors Simon_N (compatible [C] vs. incompatible [IC]), Simon_{N-1} (C vs. IC), numerical distance (ND_N, far vs. close) and ND_{N-1} (far vs. close) was conducted on RTs and error rates alike. The factor numerical distance represented a two-level factor in which the numbers 1, 2, 8, and 9 were considered far from 5, whereas the numbers 3, 4, 6, and 7 were classified as close to 5 (see also Oriet et al., 2005). Results are shown in the Appendix in Table A1.

As expected, we found a reliable Simon effect of 22 ms, $F(1, 14) = 51.34$, $MSE = 560.80$, $p < .001$, $\varepsilon = .786$, as well as a typical effect of numerical distance (30 ms), $F(1, 14) = 43.93$, $MSE = 1{,}243.98$, $p < .001$, $\varepsilon = .758$. Both factors did not interact ($F < 1$).

The Simon effect was larger after Simon-compatible trials (36 ms) and was virtually eliminated, although significant (8 ms), $t(14) = -2.26$, $p < .05$, after Simon-incompatible trials. This sequential modulation, $\text{Simon}_N \times \text{Simon}_{N-1}$, $F(1, 14) = 47.91$, $MSE = 255.08$, $p < .001$, $\varepsilon = .774$, (see Figure 1A, right panel) may be attributed to adaptive control mechanisms regulating behavior after the detection of response conflict (Botvinick et al., 2001; Gratton et al., 1992; Wühr, 2005; Wühr & Ansorge, 2005; but see Hommel et al., 2004).[3]

Most important for the present study, the Simon adaptation effect (the interaction $\text{Simon}_N \times \text{Simon}_{N-1}$) was modulated by the ND-induced processing demands in trial $N - 1$, as suggested by the reliable three-way interaction between $\text{Simon}_N \times \text{Simon}_{N-1} \times \text{ND}_{N-1}$, $F(1, 14) = 15.52$, $MSE = 105.86$, $p < .005$, $\varepsilon = .526$. Consistent with the expected $\text{ND}_{N-1} \times \text{Simon-modulation}_N$ interaction, Simon-induced conflict adaptation was less pronounced when digits close to the criterion were categorized in trials $N - 1$ (increased ND-induced task demands for the primary task) compared to the categorization of digits far from the criterion in trials $N - 1$ (see Figure 1B).

The activation of control adjustments after Simon conflict also affected the efficiency of the subsequent processing mode, which was confirmed by the interaction between Simon_{N-1} and ND_N, $F(1, 14) = 33.17$, $MSE = 50.32$, $p < .001$, $\varepsilon = .703$. Interestingly, the ND effect was larger after trials with response conflict (35 ms) than after trials with no response conflict (25 ms). As can be seen in Figure 2A (right panel), previous conflict slowed primarily the controlled comparison process, which eventually resulted in a three-way interaction between $\text{ND}_N \times \text{ND}_{N-1} \times \text{Simon}_{N-1}$, $F(1, 14) = 12.16$, $MSE = 81.87$, $p < .01$, $\varepsilon = .465$ (see also Figure 2B).

Irrespective of response conflict, a sequential modulation was also observed for the ND effect. That is, the ND effect increased after categorizing numbers that were far from the standard (40 ms) compared to conditions, in which close numbers were categorized in trial $N - 1$ (20 ms), resulting, as hypothesized, in an interaction between $\text{ND}_{N-1} \times \text{ND}_N$, $F(1, 14) = 29.19$, $MSE = 195.82$, $p < .001$, $\varepsilon = .676$ (see Figure 2A, left panel).

Further significant results include an effect of Simon compatibility in trial $N - 1$ on RTs in trial N, $F(1, 14) = 23.02$, $MSE = 90.35$, $p < .001$, $\varepsilon = .622$. That is, previous response conflict prolonged RTs in trial N. Finally, a significant interaction between all factors (Simon_N, Simon_{N-1}, ND_N, and ND_{N-1}) was found, $F(1, 14) = 53.61$, $MSE = 75.04$, $p < .001$, $\varepsilon = .793$ (see Appendix).

A repeated measures ANOVA conducted on the error data contained the same factors as the ANOVA on RTs. More errors were committed in Simon-incompatible conditions (4.6%) compared to Simon-compatible conditions (2.2%), $F(1, 14) = 16.42$, $MSE = 20.78$, $p < .005$, $\varepsilon = .540$. Also, the error data mirrored the sequential modulation of the Simon effect found for the RT data. That is, the factors Simon_N and Simon_{N-1} interacted significantly, $F(1, 14) = 23.34$, $MSE = 14.19$, $p < .001$, $\varepsilon = .625$. Furthermore, the Simon effect in the error data was larger when far numbers (3.2%) rather than close numbers (1.6%) were categorized in trial $N - 1$, $F(1, 14) = 9.58$, $MSE = 3.77$, $p < .01$, $\varepsilon = .406$. Far numbers in the current trial, however, led to a smaller Simon effect than did close numbers, $F(1, 14) = 5.46$, $MSE = 17.49$, $p < .05$, $\varepsilon = .281$. Similarly, the sequential modulation of the Simon effect was less pronounced for far numbers in N (2.5% to −0.3%) than for close numbers in N (6.9% to 0.3%). This was shown in the three-way interaction between Simon_N, Simon_{N-1}, and ND_N, $F(1, 14) = 17.26$, $MSE = 3.13$, $p < .005$, $\varepsilon = .552$. At the same time, no interaction was found between the factors Simon_N, Simon_{N-1}, and ND_{N-1} ($F < 1$).

ND also affected error rates. That is, error rates were higher for numbers close to the criterion (5.2%) than for numbers far from the criterion (1.7%), $F(1, 14) = 30.37$, $MSE = 24.13$, $p < .001$, $\varepsilon = .684$. Like in the RT data, the size of the ND_N effect was modulated by ND_{N-1}, $F(1, 14) = 8.02$, $MSE = 8.67$, $p < .05$, $\varepsilon = .364$. Furthermore, ND_{N-1} affected error rates in general, with more errors being committed when the previous number was far (4.0%)

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[2] None of the results changed when identical repetitions were included in the analyses.

[3] This sequential modulation of the Simon effect in particular (as well as all other effects) was neither changed when excluding all stimulus repetitions, $F(1, 14) = 65.14$, $MSE = 257.91$, $p < .001$, $\varepsilon = .823$, nor affected by the additional factor response repetition (repetition vs. change; $F < 1$). Although it is hard to safely exclude any involvement of repetition priming, these analyses suggest that such an involvement, if any, is rather negligible for the present study.

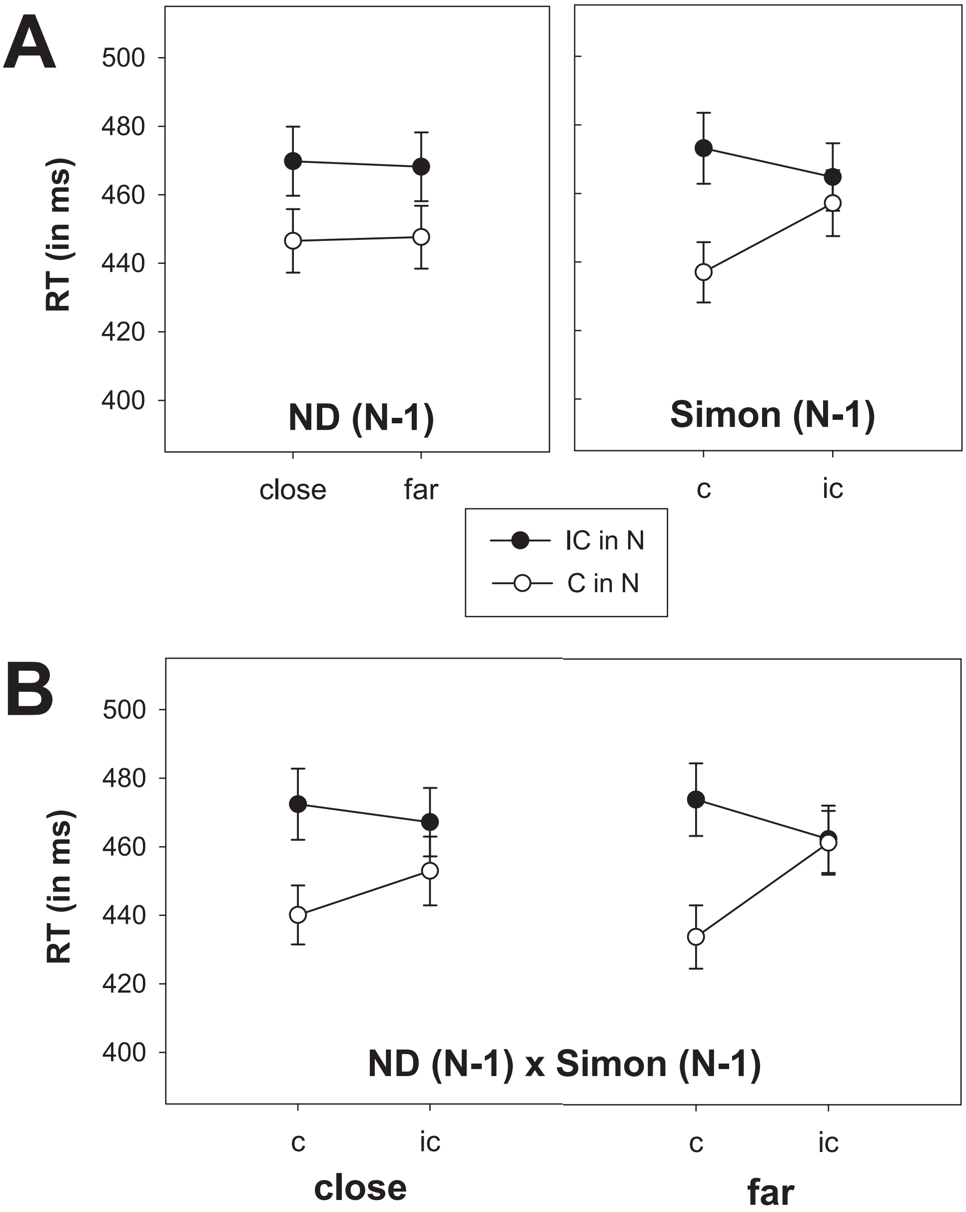

Figure 1. Modulations of the Simon effect in trial *N*, represented by mean reaction times (RTs). Panel A shows the size of the Simon effect as a function of previous numerical distance (ND; left side) and as a function of previous Simon compatibility (right side). Panel B shows the sequential modulation of the Simon effect as a function of both previous response conflict and previous ND. Error bars represent standard errors of the mean. c = compatible; ic = incompatible.

than close (2.8%), $F(1, 14) = 19.18$, $MSE = 4.53$, $p < .01$, $\varepsilon = .578$.

Finally, the interaction between Simon_{N-1} and ND_{N-1} in the present trial shows that the most errors were produced when in the previous Simon-compatible trial a far number was judged (4.6%) and that the least errors were committed when in the previous trial (irrespective of Simon compatibility) a close number was judged (2.8%), $F(1, 14) = 8.74$, $MSE = 2.58$, $p < .05$, $\varepsilon = .384$. Note, however, that especially the results for the higher order interactions should be taken with caution given the very low error proportions per participant and condition.

Discussion

The aim of the present research was to study different control regulation mechanisms that support the efficient processing of the currently relevant task goal and the shielding of this goal from distracting information. More specifically, we investigated the interplay between control adjustments elicited by previous response conflict from task-irrelevant stimulus information, on the one hand, and processing adjustments on the basis of previous variations in task-relevant processing demands, on the other.

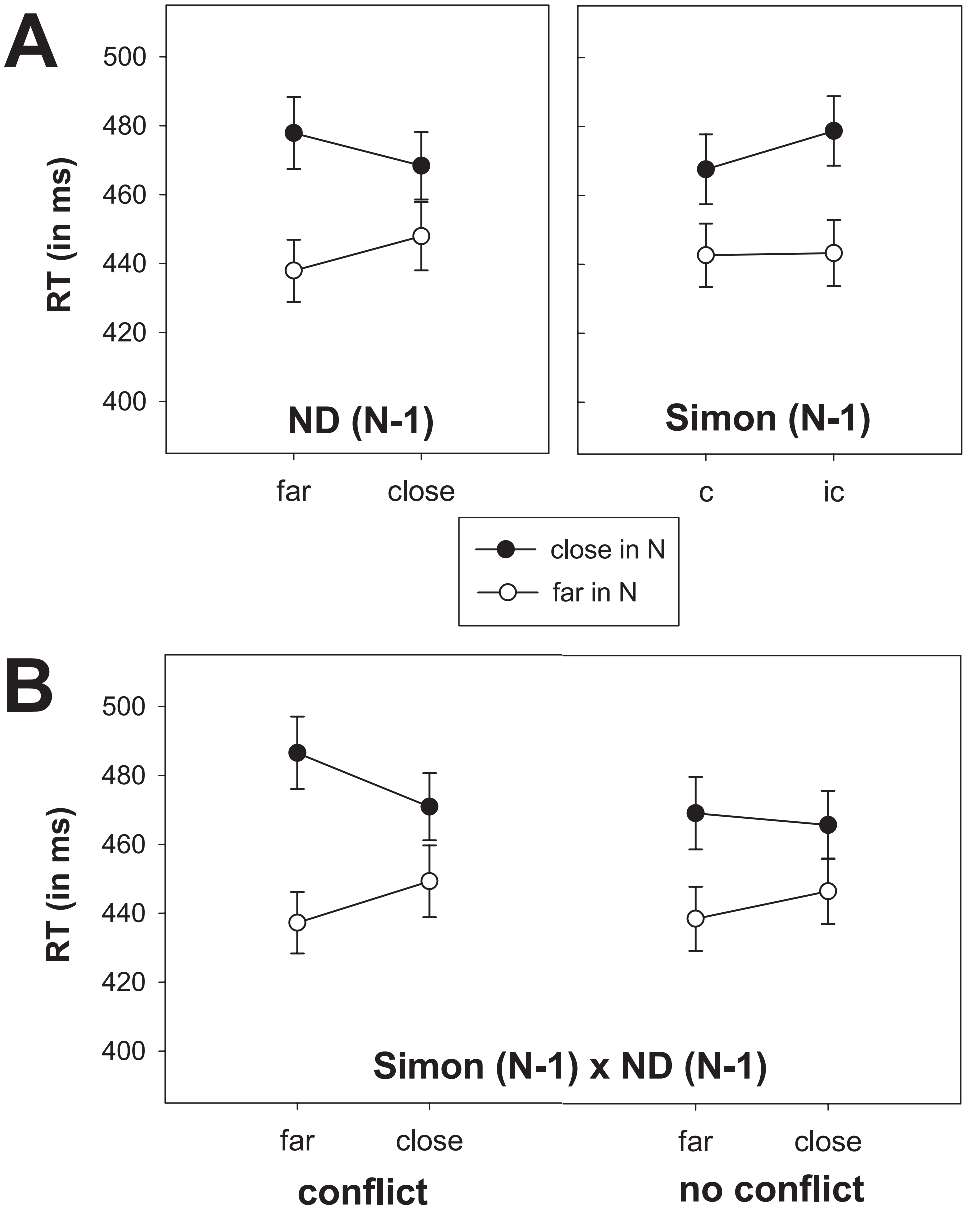

Figure 2. Modulations of the numerical distance (ND) effect in trial *N*, represented by mean reaction times (RTs). Panel A shows the size of the ND effect as a function of previous ND (left side) and as a function of previous Simon compatibility (right side). Panel B shows the sequential modulation of the ND effect as a function of both previous response conflict and previous ND. Error bars represent standard errors of the mean. c = compatible; ic = incompatible.

In this respect, the most important results of our study are the interactions between the two kinds of dynamic adaptations of cognitive control. First of all, we found typical effects of Simon compatibility and its sequential modulation, which has often been taken as evidence for conflict-induced control adjustments (Botvinick et al., 2001; Gratton et al., 1992; Wühr, 2005; Wühr & Ansorge, 2005; but see Hommel et al., 2004; Wendt, Kluwe, & Peters, 2006). In addition, we found that these control adjustments were reduced in conditions of increased control demands for the primary task in the previous trial ($\text{ND}_{N-1} \times \text{Simon-modulation}_N$). This result (see Figure 1B) shows that increased processing demands in trial $N - 1$ (classifying close numbers) affected the efficient activation of control mechanisms that serve to reduce interference from task-irrelevant stimulus features in the subsequent trial *N*. This extends previous studies by showing that not only the quantity of conflict modulates subsequent adjustments of cognitive control but, moreover, that such adjustments of cognitive control are also sensitive to specific attentional requirements of processing task-relevant stimulus features (without conflict) in trial $N - 1$ (e.g., Freitas, Bahar, Yang, & Banai, 2007).

Second, our results show not only that Simon-induced conflict in trial $N - 1$ leads to heightened control in the subsequent trial (conflict adaptation) but moreover that this control, serving to reduce interference from irrelevant stimulus attributes, negatively affects the efficiency of the number comparison process (see the $\text{Simon}_{N-1} \times \text{ND}_N$ interaction). Especially the controlled processing mode for categorizing close numbers is slowed after conflict, whereas the categorization of far numbers is not affected (see Figure 2A, right panel). To account for this result, one could assume that both mechanisms compete for the same resources. Alternatively, one could also assume that in conditions of heightened control for interference reduction, switching from judging far numbers in $N - 1$ (automatic precategorization process) to a slow and controlled comparison process in N is especially difficult.[4] Although further studies might be needed to disentangle these possibilities, the present results clearly show that the effortful number comparison mode cannot benefit from increased control for interference reduction in trial N.

Third, as predicted, we found that the size of the ND effect in trial N was modulated by the numerical distance in trial $N - 1$ ($\text{ND}_{N-1} \times \text{ND}_N$; see Figure 2A, left panel). ND effects were smaller when close rather than far digits were categorized in trial $N - 1$, indicating dynamic adjustments in cognitive control that are not related to previous response conflict. This finding is consistent with our assumption that processing demands in the number comparison judgment are increased when the judgments are based on an effortful comparison process (e.g., in the case of close numbers), whereas processing demands are decreased when size judgments are based on an automatic categorization process (e.g., in the case of far numbers; cf. Oriet et al., 2005). A repeated application of a particular categorization process will speed up the number classification only if the stimulus class is also repeated (e.g., far_{N-1}, far_N). A repeated automatic categorization process on trials in which a far number is followed by a close number, for example, will prolong RTs and increase the probability of wrong responses. Together, this results in a sequential modulation of the ND effect, which suggests that not only response conflicts due to irrelevant stimulus features but also variations in attentional demands in the primary task produce subsequent processing adjustments.

At first glance our results seem to be at odds with accounts suggesting that the processing of task-irrelevant stimulus features is blocked after conflict (e.g., Stürmer et al., 2002). Strictly speaking, if the conflict adaptation mechanism acts merely on the task-irrelevant dimensions, specific aspects of subsequent task-relevant processing should not be affected (e.g., certain qualities about number size judgments). However, our results show that a Simon conflict in trial $N - 1$ not only reduced irrelevant location interference in trial N but also affected the size judgment in trial N.

In sum, our findings confirm the idea that flexible adaptation of cognitive control serves to support the cognitive system in fulfilling the primary task and in shielding the system against distraction from irrelevant information. In the present study, we found that increased processing requirements in the primary task required resources that draw from the pool needed for the sufficient activation of control mechanisms in Simon-conflict trials. Along the same lines, an experienced (Simon_{N-1}) response-conflict triggered adjustments of cognitive control for interference reduction in the subsequent primary task that altered the subsequent number-comparison process.

Consequently, our study points to the necessity of characterizing not only the influence of task-irrelevant stimulus features leading to conflict and conflict adaptation but moreover, to integrating and regarding the specific requirements of processing task-relevant stimulus features that might also determine adjustments of cognitive control.

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[4] In this respect a further conceivable interpretation would propose a general "fluency monitoring system" that might monitor the fluency of processing or the fluency of responding. Therefore, this system might be particularly sensitive to processing alterations that slow down responses, such as response conflict (Simon), difficult processing (close numbers), committed errors, or generally outcomes that are less than expected. We thank an anonymous reviewer for directing our attention to this possibility.

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Appendix

Further Discussion of Adjustments of Cognitive Control

Table A1

Response Times in Milliseconds (Percent Error) for Simon Compatibility (Compatible [C] vs. Incompatible [IC]) and Numerical Distance (ND, Far vs. Close) in Previous ($N - 1$) and Current (N) Trials

		Simon C_{N-1}		Simon IC_{N-1}	
ND_{N-1}	ND_N	C_N	IC_N	C_N	IC_N
Close	close	454 (1.5)	478 (6.3)	460 (4.4)	482 (3.9)
Close	far	426 (0.1)	467 (3.2)	446 (1.9)	452 (1.1)
Far	close	446 (2.1)	493 (11.3)	491 (5.3)	482 (6.5)
Far	far	422 (1.5)	455 (3.5)	432 (0.8)	442 (1.1)

With respect to the ND_{N-1} × Simon-modulation$_N$ interaction, we argued that the activation of control adjustments is less sufficient when the processing mode binds resources in $N - 1$ (ND close). Inspection of these data in Table A1 might suggest that this is the case only when ND is close in trials $N - 1$ and N (see row 1). However, it does not appear plausible that attentional limitations in trial N are responsible for this insufficient control adjustment because control adjustments also lead to strong sequential modulations in the conditions far ND_{N-1} and close ND_N (see row 3).

Received August 4, 2007
Revision received January 28, 2008
Accepted January 31, 2008 ■